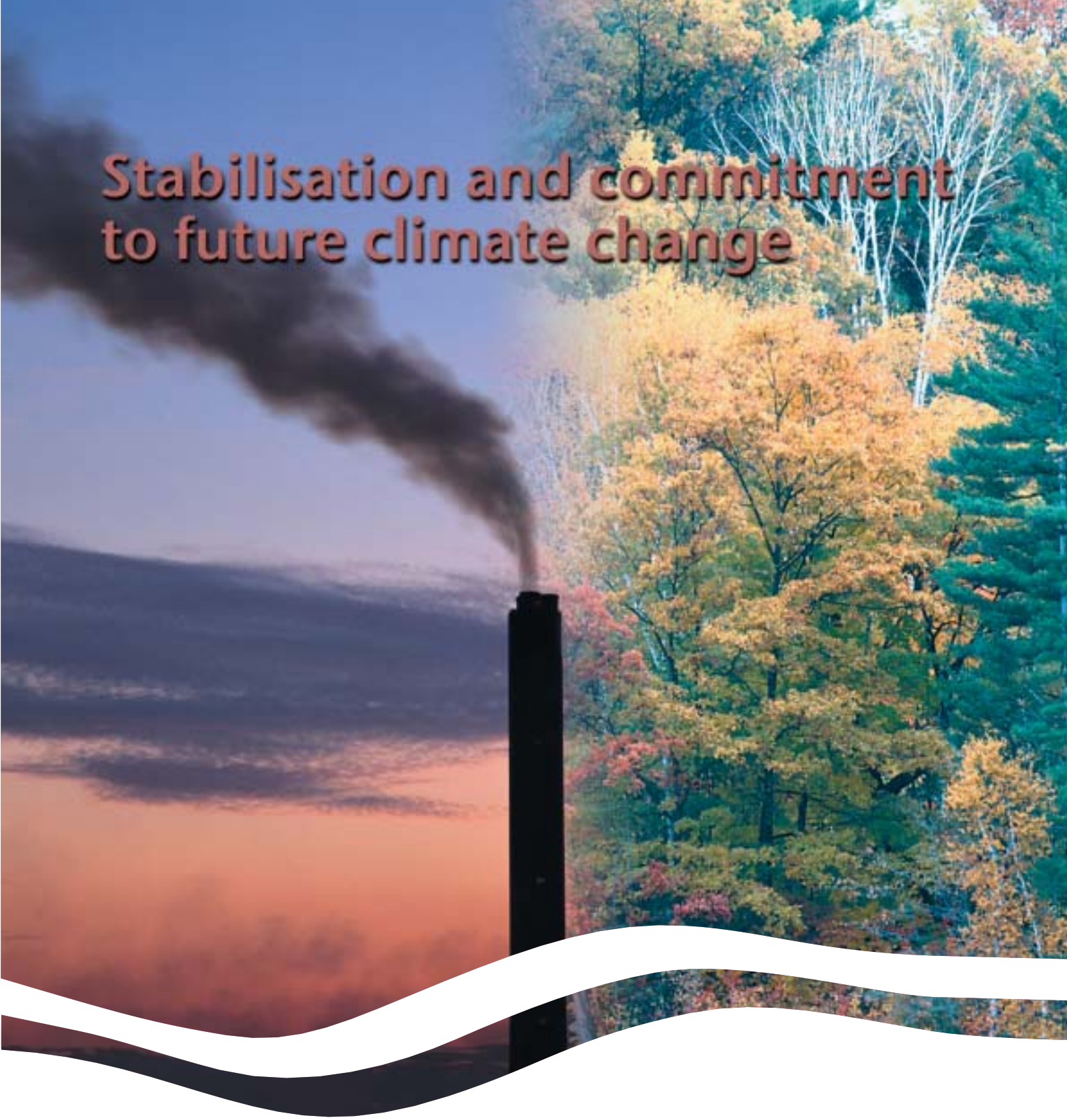


Stabilisation and commitment to future climate change

Scientific results from the Hadley Centre

October 2002

defra
Department for Environment Food and Rural Affairs

Met Office

In this report

The ultimate objective of the UN framework convention on climate change (UNFCCC) is to stabilise atmospheric concentrations of greenhouse gases 'at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system'. In this report, we focus on some of the scientific issues associated with this aim, including the following.

■ Physical commitment to climate change

Even if atmospheric greenhouse gas concentrations were stabilised immediately, we could still experience a changing climate and sea-level rise for more than 1,000 years into the future due to past emissions. Furthermore, the greenhouse gases we emit today and in the near future will initiate changes in climate that will be felt far into the future.

■ Predictions of climate change when carbon dioxide concentrations are stabilised in the future

Reducing carbon dioxide (CO_2) emissions so that concentrations approach stabilisation will delay the amount of climate change we experience over the next 100 years and more. However, any realistic future stabilisation level is likely to result in some damage.

■ The effect of the carbon cycle on stabilisation of atmospheric CO_2 concentrations

When the feedbacks between the climate system and the carbon cycle are taken into account, such as the increased emission of CO_2 from soils as temperature rises, the anthropogenic emissions consistent with a particular stabilisation level of greenhouse gas concentrations are lower than previously thought.

In addition, we include a short climate bulletin, highlighting recent observed changes in climate.

Introduction

Ten years since the Rio Earth Summit

In the 10 years since the Rio Earth Summit, our understanding of the climate system — and the degree of certainty that mankind has already caused the climate to warm — have both increased. The Intergovernmental Panel on Climate Change (IPCC) now accepts that 'there is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities'.

The power of computers and our ability to simulate the climate system have also improved dramatically. The models we now use to make projections of future climate routinely include the dynamics of the atmosphere and the ocean, and many physical processes, such as the effects of clouds and the cooling effects of the atmospheric sulphur cycle. The most sophisticated simulations also include atmospheric chemistry and the carbon cycle, and their response to climate change.

In the IPCC's recent third assessment report, to which the Hadley Centre was a major contributor, the global average temperature between 1990 and 2100 is projected to rise by 1.4 °C to 5.8 °C, and the mean sea level is predicted to rise by 9 cm to 88 cm. At some locations, the increases will be larger than the global average, but at others it will be smaller. It is also becoming clear that extremes of climate, which are often responsible for most of the damage, are likely to change in the future.

In this report, we highlight areas of recent research that demonstrate the long timescales associated with climate change and how the response of the climate to future anthropogenic emissions may be strongly dependent on changes in the biosphere.

The Hadley Centre

The Met Office's Hadley Centre for Climate Prediction and Research is charged by Government with undertaking research into climate change.

The Hadley Centre provides a focal point in the UK for the scientific issues associated with climate change. Currently, the centre employs some 100 scientific and technical experts, and has access to two Cray T3E supercomputers. It is supported by the Department for Environment, Food and Rural Affairs (DEFRA), other government departments and the European Commision.

The aims of the Hadley Centre are:

- to understand physical, chemical and biological processes within the climate system and develop state-of-the-art climate models that represent them;
- to use climate models to simulate global and regional climate variability and change over the past 100 years, and to predict changes over the next 100 years or more;
- to monitor global and national climate variability and change;
- to attribute recent changes in climate to specific factors; and
- to understand the natural interannual-to-decadal variability of climate, with the aim of forecasting it.

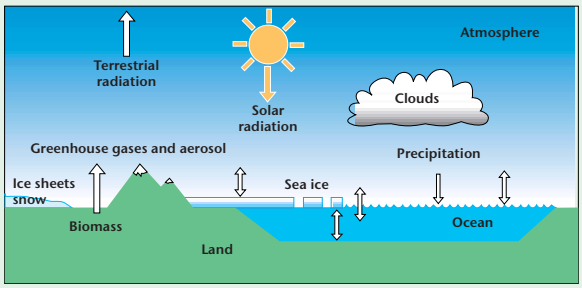
The current Hadley Centre building in Bracknell. In late 2003, the staff of the Hadley Centre will move, together with the rest of the Met Office, to a new building in Exeter, in the south-west of England.

Physical commitment to climate change

The meaning of commitment

The climate system has many different components and these respond on different timescales. When increases in greenhouse gas concentrations lead to an imbalance between the incoming visible energy from the sun and outgoing energy from the earth, there is net flow of heat into the atmosphere. Gradually, the climate system warms; this increases the amount of energy leaving it until, eventually, a new balance occurs at a higher temperature. Although the atmosphere can respond relatively quickly to changes in greenhouse-gas heating, the ocean and ice caps respond more slowly. For instance, parts of the deep ocean can take more than 1,000 years to respond to a surface greenhouse warming. As a consequence, even if greenhouse gas concentrations were stabilised immediately, the global temperature and sea level would continue to rise for a considerable amount of time into the future. This is the physical commitment to climate change.

Global climate models



Global climate models (often called general circulation models, or GCMs) simulate processes in the atmosphere, ocean and on the land. The atmospheric component consists of a three-dimensional representation of the atmosphere coupled to the land surface and cryosphere. The atmosphere model is similar to those used for weather forecasting but, because it has to produce projections for decades or centuries rather than days, it uses a coarser level of detail. The ocean component of the models consists of a three-dimensional representation of the ocean and of sea ice. Global climate models typically have a horizontal resolution of a few hundred kilometres. Processes operating on smaller scales are represented through relationships with the larger scales.

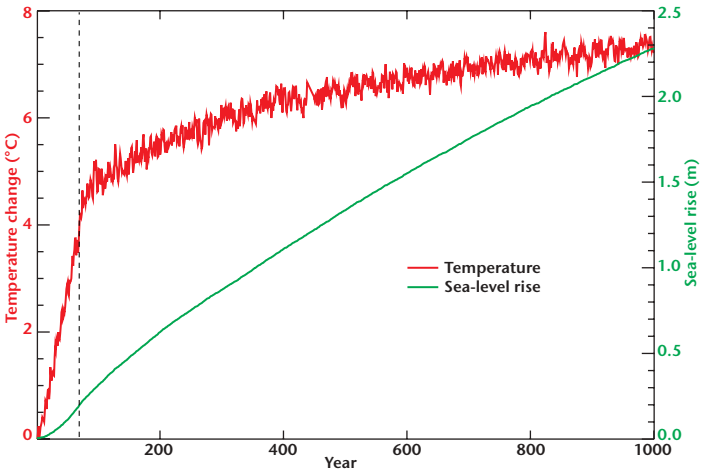
Climate models include the cooling effects of sulphate aerosol particles. The most recent models also include aspects of the biosphere, carbon cycle and atmospheric chemistry.

Global climate models are used to simulate past climates and to predict future climates. They are also used to study natural variability and the physical processes of the coupled climate system.

How do we calculate the physical commitment?

In order to calculate the commitment to climate change, we estimated the response times of the climate system for atmospheric temperature changes, and the strength of this response, using a 1,000-year simulation from the Hadley Centre's third-generation global climate model (see box).

In this idealised model experiment, the carbon dioxide concentrations were increased from pre-industrial levels to four times pre-industrial levels over a period of 70 years, and then held constant for the remainder of the experiment (below).

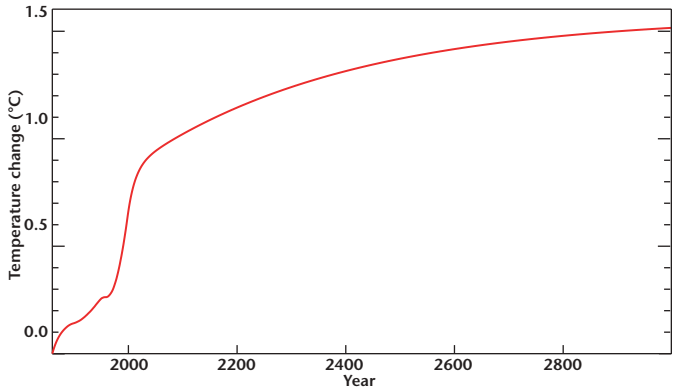


Simulated temperature change and the thermal-expansion component of sea-level rise for the four times pre-industrial CO_2 concentration ($4xCO_2$) experiment. Global temperatures stabilise quicker than sea level, which is still rising after 1,000 years. We estimate that it would take more than 2,500 years before the sea level reaches 90% of its final value. The dashed line shows the year when CO_2 concentrations were stabilised.

In order to estimate what would happen to temperature in the real climate, if we were to stabilise concentrations of greenhouse gases, we combined the climate response times and the strength of response from the $4xCO_2$ experiment with observed increases in greenhouse gas concentration over the past 150 years or so. The dashed line shows the year when CO_2 concentrations were stabilised.

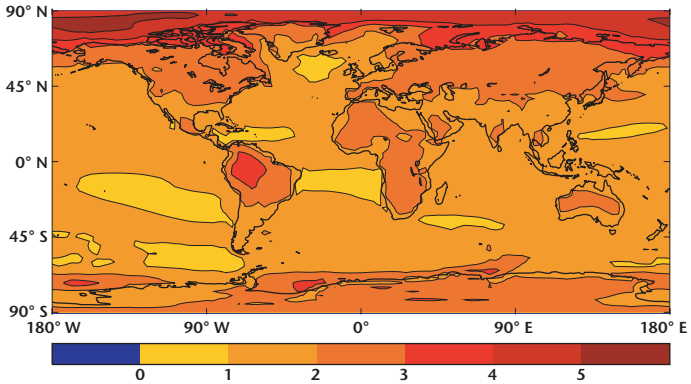
How big is the current physical commitment?

If we were able to stabilise greenhouse gas concentrations today then we estimate that, by 2100, the temperature would rise by around 1.1 °C relative to pre-industrial times, and is predicted to rise to 1.6 °C eventually (below).



The rise in global mean temperature following stabilisation of greenhouse gas concentrations at present-day levels.

We have estimated the regional commitment to climate change by scaling the pattern of temperature rise from the $4xCO_2$ simulation with our estimate of global mean temperature-rise commitment (below). The commitment to temperature change will not be the same everywhere and, relative to pre-industrial times, some locations may eventually warm by as much as 5 °C due to the increases in greenhouse gas concentrations that have already occurred.

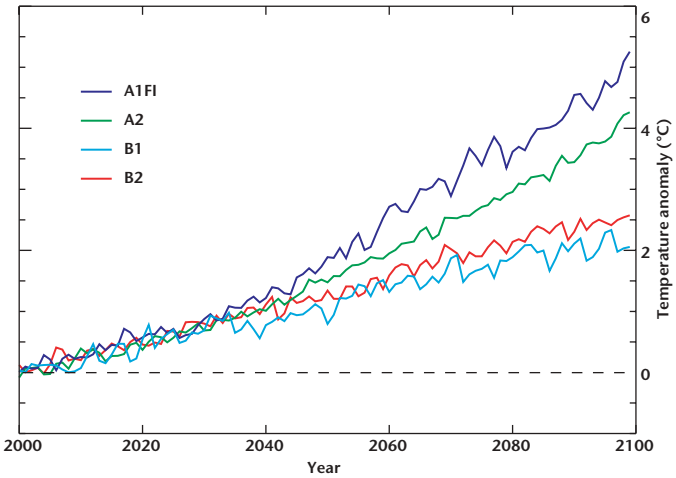


Patterns of annual average temperature-rise commitment (°C) due to anthropogenic emissions prior to present day.

Lessons from the SRES emissions scenarios

The SRES emissions scenarios, published by the IPCC in 2000, have formed the basis of many of the projections of climate change in the IPCC Third Assessment Report. They have very different pathways, with A1FI rising sharply from today's value of 7 GtC of carbon emissions up to a final value of about 30 GtC by 2100. At the other extreme, the B1 scenario rises slowly to a peak of 9 GtC by mid-century and then falls to below 5 GtC by 2100.

When these scenarios are used to drive the Hadley Centre climate model, the resulting predictions (below) tell an interesting story. Until about 2040, the temperature rise predicted for all four scenarios (A1FI, A2, B2, B1) follows very similar paths; the difference between them is mainly due to natural variability.



Predicted temperature change due to various SRES scenarios, expressed relative to present day.

This similarity is partly because all four have built into them the physical commitment to change due to emissions today and over past decades. In addition to this 'legacy' effect, inertia in the climate system delays the response to the very different future emissions, and hence the effect of these is not immediately apparent. By the end of the century, however, the warmings are very different: 2 °C for B1 and 5 °C from A1FI emissions, expressed relative to present day. This shows that the degree of late-century warming is greatly influenced by levels of emissions over the next few decades. In the case of the lowest (B1) emissions scenario, about one-quarter of the change during the 21st century is due to the physical commitment to emissions prior to today.

Conclusion

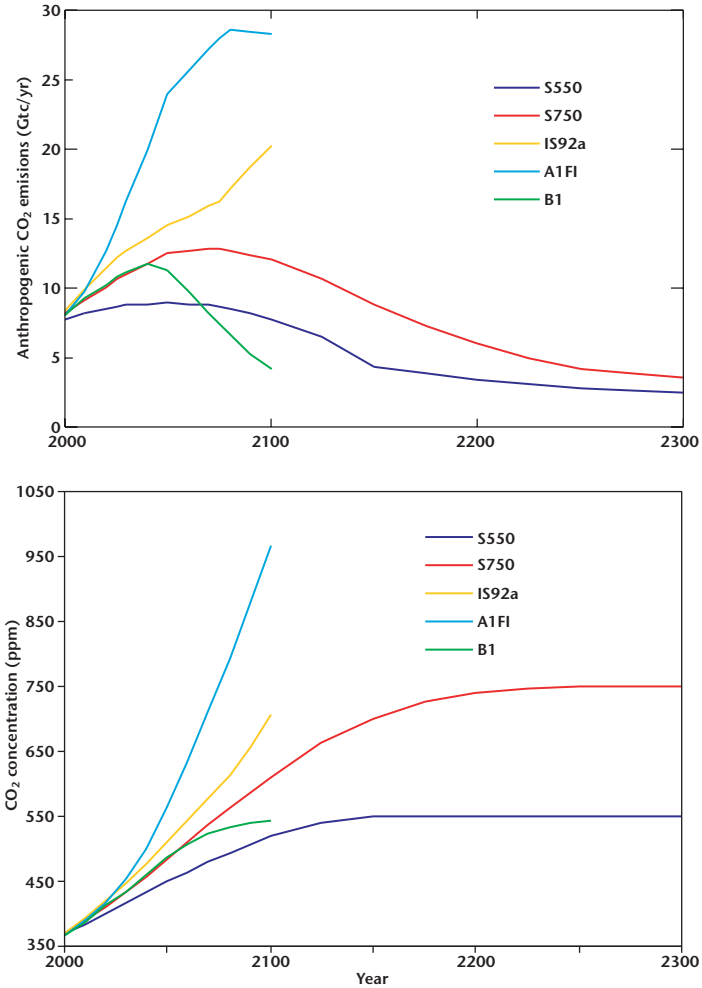
We are already committed to a sizeable warming and sea-level rise. Furthermore, the increases in greenhouse gas concentration caused by human emissions between present day and 2100 will themselves lead to an additional long-term warming and sea-level rise commitment far into the future.

Predictions of climate change when CO_2 concentrations are stabilised in the future

The emissions scenarios

In 1997, the Intergovernmental Panel on Climate Change (IPCC) suggested a number of emissions scenarios that include reductions relative to the 'business as usual' case, and which ultimately stabilise atmospheric carbon dioxide concentrations. We have examined the climate change for scenarios that stabilise CO_2 concentrations at 750 parts per million (ppm) and 550 ppm, about twice present-day and twice pre-industrial levels, respectively. It is important to note that, in the foreseeable future, stabilisation of CO_2 concentrations is not the same as either the stabilisation of emissions, or of climate change. Furthermore, other greenhouse gases have to be stabilised too.

The profiles of anthropogenic emissions of CO_2 which can achieve the IPCC stabilisation levels[1] (below, upper panel) are very much less than the emissions for the 'business as usual' scenario (IS92a) or the newer SRES A2 scenario. The greenhouse gas concentrations (below, lower panel) for the lowest of the SRES scenarios (B1) lies close to or between the 550 ppm and 750 ppm concentration curves for much of the 21st century.



Anthropogenic CO_2 emissions (top panel) and atmospheric CO_2 concentrations (bottom panel).

Predicting climate change

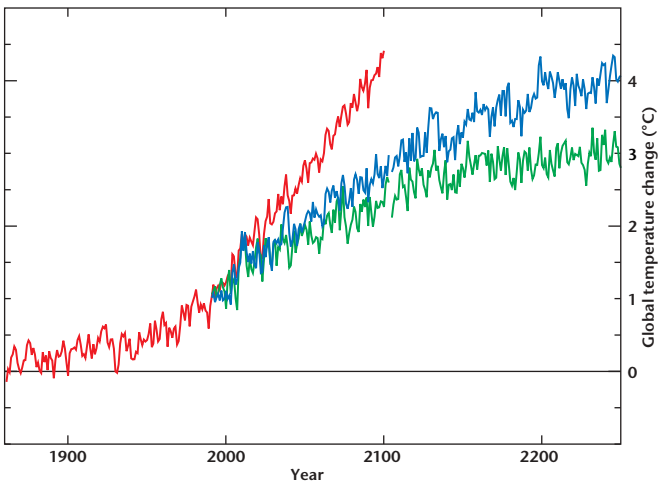
In order to compare the climate change resulting from the 550 ppm and 750 ppm stabilisation scenarios with the climate response to an unmitigated (IS92a) scenario, the Hadley Centre climate model has been used to simulate each of the three cases. Some of these results were shown previously in the report published for CoP5.

For simplicity, the climate model was driven with CO_2 emissions only and did not explicitly include changes in other greenhouse gases or aerosols. The simulations here also did not include the feedback between the carbon cycle and climate change, but these effects are discussed on pages 6 and 7.

The climate change under CO_2 stabilisation scenarios

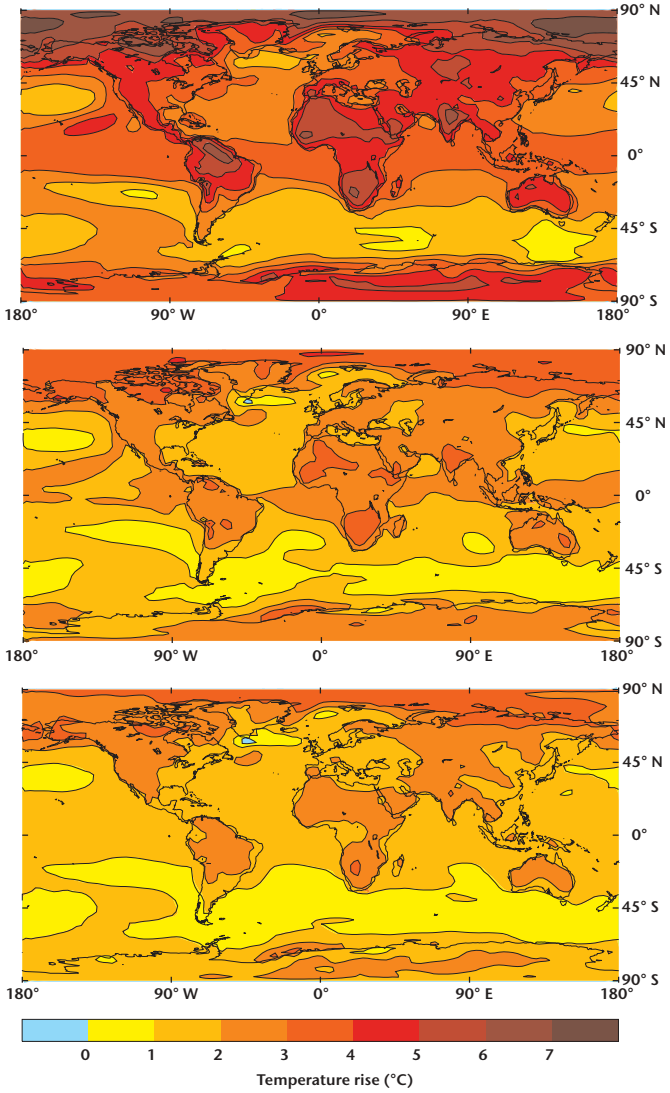
With unmitigated emissions, temperatures by the 2080s are predicted to be about 3 °C above today's (taken as the average over the period 1961–90). A global average temperature rise of 2 °C, which would occur by the 2050s with unmitigated emissions, will be delayed by about 50 years under 750 ppm stabilisation, and by over 100 years under 550 ppm stabilisation. By 2250, global temperatures will have risen to just over 2 °C above today's under the 550 ppm stabilisation scenario, and just over 3 °C under the 750 ppm scenario.

The pattern of temperature change by the 2080s is similar for all three emissions scenarios, with a magnitude roughly proportional to global temperature



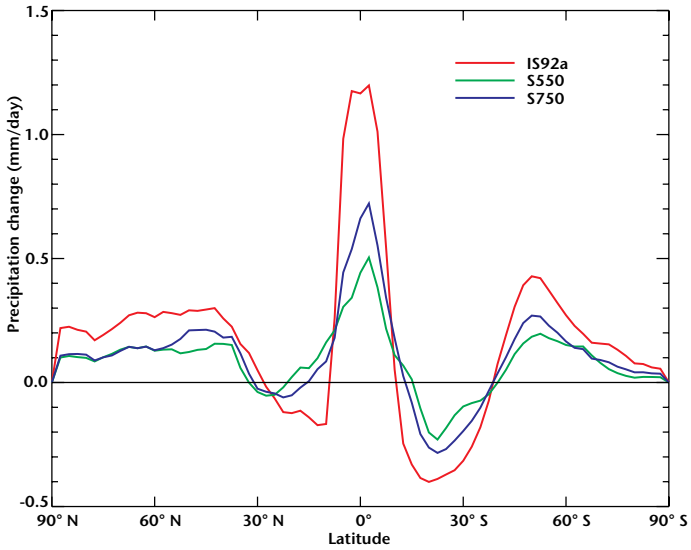
The global average temperature rise resulting from the unmitigated emissions scenario (red), and emissions scenarios which stabilise CO_2 concentrations at 750 ppm (blue) and at 550 ppm (green).

change. For both the stabilisation and unmitigated scenarios, land areas will warm almost twice as fast as oceans, and winter high latitudes are also expected to warm more quickly than the global average, as are areas of northern South America, India and southern Africa (below).



Patterns of annual average temperature rise from the present day to the 2080s, resulting from the unmitigated emissions scenario (top), an emissions scenario which stabilises CO_2 at 750 ppm (middle) and one which stabilises at 550 ppm (bottom).

The changes in precipitation (both positive and negative) by the 2080s are largest in the Tropics, but significant changes do occur in mid- and high-latitude regions (below). The magnitude of changes is again smaller for the stabilisation scenarios than for the unmitigated scenario and are roughly proportional to global temperature rise.



Zonally averaged annual mean precipitation changes (2080s minus present day) in IS92a, S750 and S550 scenarios.

The changes in temperature and precipitation will have impacts on society across the globe. In some regions, the warmer temperatures and reduced precipitation will make water scarce and the growing of crops more difficult. In other areas, increases in precipitation (and the fraction of precipitation that falls in the most intense storm events) will contribute to more frequent flooding by rivers. At the coast, increases in sea level and changes in storminess will lead to inundation of unprotected land, more frequent flooding by storm surges and the loss of coastal wetlands. However, not all regions will be adversely affected. Increases in CO_2 concentrations will enhance crop production in some locations, and increases in precipitation will improve the situation in some regions where water is currently scarce.

Conclusion

Much of the climate change and consequent impacts resulting from unmitigated emissions of CO_2 will be delayed by 50 to 100 years, if emissions scenarios leading to stabilisation of CO_2 are followed. In addition, stabilisation of CO_2 at 550 ppm or less may even prevent some of the more serious impacts from occurring.

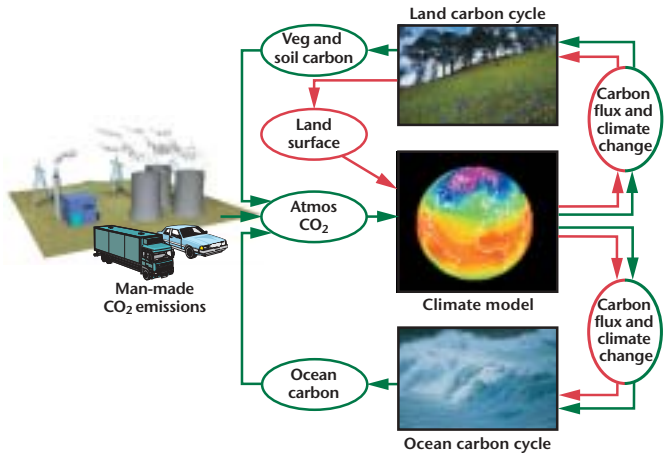
[1]There are an infinite number of pathways in which emissions can be reduced in order to stabilise concentrations in the atmosphere. The two most widely used are the IPCC 'S' scenarios and the 'WRE' scenarios. In the WRE scenarios, the emissions deviate from a 'business as usual' scenario later and peak at a higher level than in the IPCC cases.

The effect of the carbon cycle on stabilisation of atmospheric CO_2 concentrations

The carbon cycle

The concentration of CO_2 in the atmosphere depends on the amount emitted — for instance, from the burning of fossil fuels and changes in land use — and the strength of carbon sinks, such as the ocean and biosphere, which remove CO_2 from the atmosphere.

As the atmospheric concentration of CO_2 increases, so does the ability of vegetation to take up CO_2 from the atmosphere (the carbon fertilisation effect). However, the increases in CO_2 lead to changes in temperature and rainfall, which can affect natural carbon sinks. Over land, climate change can alter the geographical distribution of vegetation and hence its ability to store CO_2. In the Hadley Centre coupled climate–carbon cycle model, we find that climate change results in a dying-back of the vegetation in northern South America. Climate change also affects the amount of CO_2 emitted by bacteria in the soil. In the ocean, changes in circulation and mixing, which accompany climate change, alter the ocean's ability to take up CO_2 from the atmosphere. In addition, the warmer oceans absorb less CO_2.



Schematic of a coupled climate–carbon cycle model. Green lines indicate carbon fluxes while red lines indicate physical changes and climate change.

In order to include all of these feedbacks, it is necessary to treat the carbon cycle and vegetation as interactive elements in full global climate modelling (GCM) experiments. This approach was pioneered by the Hadley Centre and the first results were reported at CoP6.

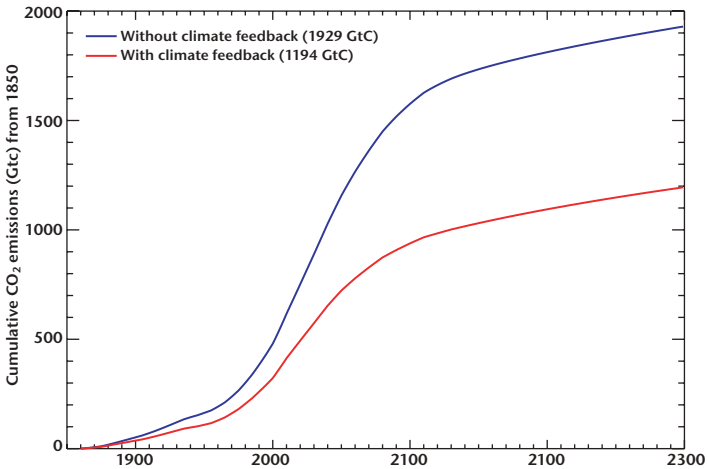
Stabilisation of CO_2 concentration at 550 ppm

On pages 4 and 5 of this report, CO_2 emissions profiles that can stabilise atmospheric concentrations of CO_2 at specific levels were discussed. We noted that, in principle, there are an infinite number of emissions pathways that lead to stabilisation of atmospheric CO_2 concentrations at a given level.

IPCC technical note 3 discussed two alternative emissions pathways which would stabilise CO_2 concentrations at a particular level: the IPCC 'S' emissions, and the emissions estimated by Wigley, Richels and Edmonds, the 'WRE' emissions. These emissions were calculated using a simple carbon cycle model that took account of the carbon fertilisation effect, but other feedbacks — such as that associated with the change of vegetation patterns or the oceans, due to climate change — were not included. To investigate such effects we used a simple climate carbon-cycle model, which includes the feedbacks from vegetation, soils and the ocean. This reproduces the results of the full Hadley Centre coupled climate–carbon cycle model, and was used to make new estimates of:

(i) the emissions required to stabilise CO_2 concentrations at 550 ppm; and

(ii) the concentrations resulting from the WRE emissions scenarios.

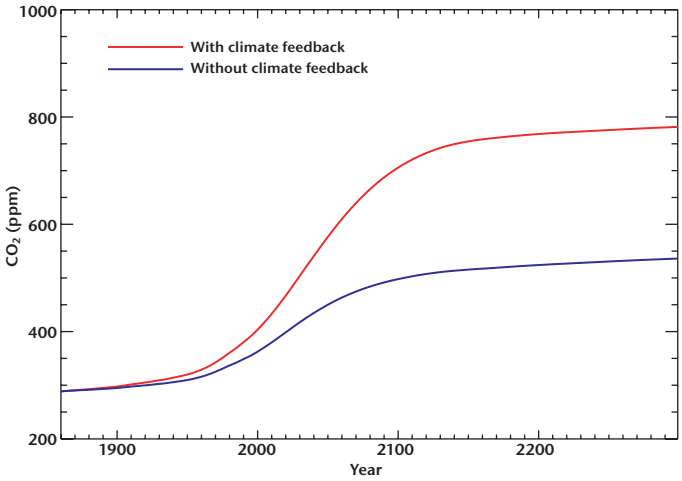


Cumulative emissions that are consistent with the WRE550 CO_2 concentration scenario.

The figure above shows two cumulative emissions profiles that eventually stabilise CO_2 at 550 ppm. The blue line shows the result from the Hadley Centre model without any carbon cycle feedbacks. The results are similar to the original WRE emissions scenario. The red line shows the result when the carbon cycle feedback is included. Thus, emissions may need to be reduced by much more than originally thought to meet a specific concentration level.

We can look at this result from the opposite direction, that is, by starting from the same emissions scenario (WRE550 in this case) and calculating the CO_2 concentrations that would result. Without including the

feedbacks, the emissions eventually lead to stabilisation of CO_2 concentration at around 550 ppm, as intended (below). However, when the more comprehensive feedbacks are taken into account, the CO_2 concentration rises much higher — to 780 ppm by 2300. Thus, the effect of carbon-cycle feedbacks is to allow a greater fraction of CO_2 emissions to remain in the atmosphere.



Impact of carbon cycle feedbacks on CO_2 stabilisation concentration for WRE550 emissions.

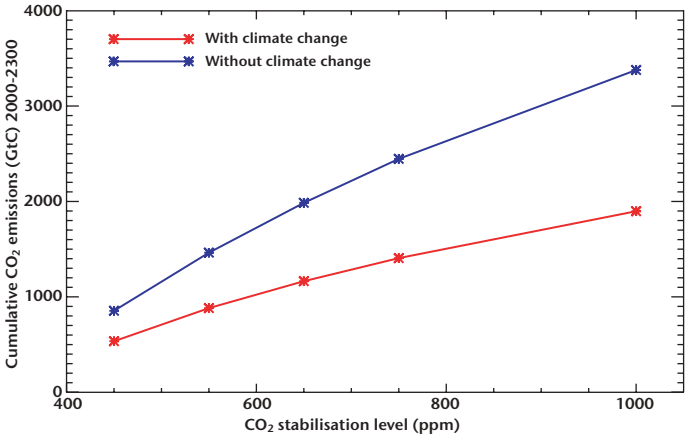
Stabilisation at other concentration levels

Stabilisation at other concentration levels has also been considered. The figure (top, right) shows the relationship between cumulative carbon emissions (from present day to 2300) and the eventual stabilisation level. The blue line shows how much the cumulative emissions would need to be in order to stabilise CO_2 at different levels. However, when the carbon cycle feedbacks are included, the 'allowable' emissions are greatly reduced for all stabilisation concentration levels (red line). For example, if we chose to stabilise at 750 ppm, the estimate of cumulative emissions is around 2,500 GtC when the feedback is not included but, with carbon cycle and vegetation feedbacks, only 1,400 GtC would be required.

Change in the storage of carbon on land

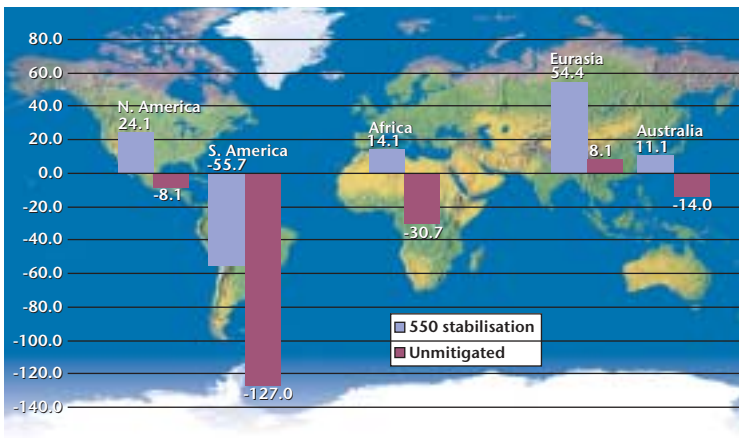
In order to show how the storage of carbon on land (in vegetation and the soil) changes in the future in the Hadley Centre model with interactive carbon cycle and vegetation, the change in land carbon between present day and 2100 has been estimated for different regions for the 550 ppm stabilisation scenario and, for comparison, an unmitigated (IS92a) scenario.

Globally, the land carbon store increases by almost 50 GtC over the century when emissions follow a stabilisation pathway, because both soil-carbon and vegetation-carbon stores increase. But, when emissions continue on an



Impact of carbon cycle feedbacks on stabilisation levels.

unmitigated course, the carbon store decreases by about 170 GtC. This is because increased soil respiration, and a die-back of vegetation in South America, together exceed the increases in vegetation storage in other regions (below). Note that the change in the natural terrestrial carbon cycle from a sink to a source by the end of the century with unmitigated emissions means that, instead of the current situation where it offsets man-made emissions, in future it could amplify the contribution from human activities.



Change in land carbon storage with climate carbon cycle feedbacks between 2000 and 2100.

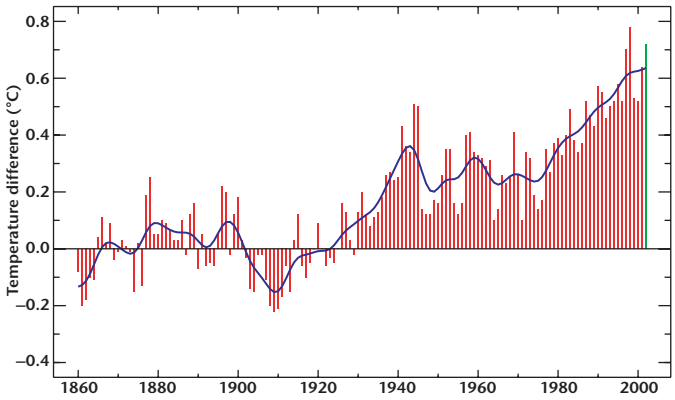
Conclusion

Preliminary calculations show that including the feedbacks between climate change and the carbon cycle greatly reduces the 'allowable' emissions that lead to CO_2 concentration stabilisation at a given level. It does this by reducing the strength of carbon dioxide sinks.

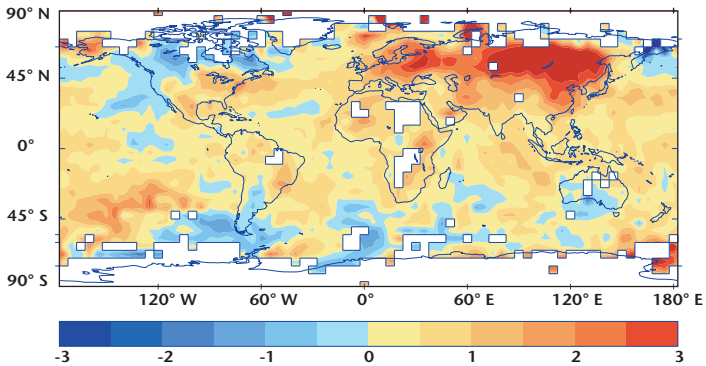
Climate Bulletin 2002

The global mean surface temperature in 2001 was approximately 0.63 °C above the average for the late 19th century. Despite the mitigating influence of the La Niña cool event in the eastern and central tropical Pacific for part of the year, it was the second warmest year on record. The 10 warmest years have all occurred since 1983, with eight of them since 1990.

The year 2002 has continued this warming trend, with the first six months of the year being the warmest on record in the northern hemisphere and the second warmest globally.

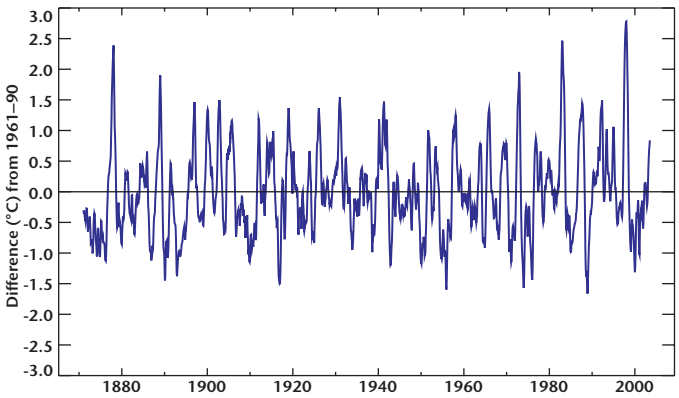


Annual combined land-surface air and sea-surface temperature anomalies (°C) for the period 1860 to June 2002. The anomaly for 2002 is based on the average anomalies between January and June.



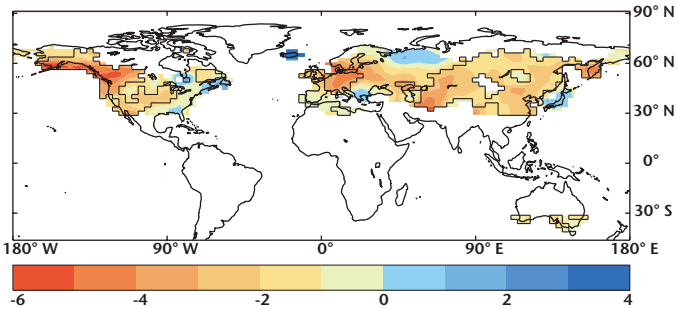
Surface temperature anomalies (°C) relative to 1961–90 for the six-month period January to June 2002.

Global average temperatures tend to be elevated during large El Niño events and lowered during La Niñas. El Niños — and the large circulation changes associated with them — also affect other climate variables, such as rainfall, over a very wide area. The warmest full year on record, 1998, coincided with the most recent large El Niño. Measurements of surface temperature patterns show that we have recently entered a new El Niño phase, but it is not yet clear how large this event will be (top right).



Equatorial Pacific sea-surface temperatures (°C) relative to 1961–90, for 1871 to August 2002.

Extremes of temperature have also changed in recent times. Using a data set collected during the 45 years from 1950 to 1995, it appears, for instance, that there has been a significant reduction in the number of frost days over most of the northern hemisphere mid-latitude land mass. The most notable exception is an increase over Iceland (below).



Change over a decade in the observed number of frost days per year, estimated from the 1950–95 data set. Black lines enclose regions where trends are significant at the 5% level.

Staff at the Met Office's Hadley Centre: September 2002

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